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AUTOMATIC ARRAY AND NETWORK DETECTION IN THE PRESENCE OF SIGNAL VARIABILITY

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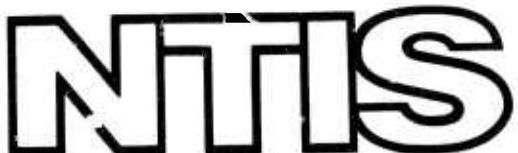
AUTOMATIC ARRAY AND NETWORK DETECTION IN THE PRESENCE OF SIGNAL VARIABILITY

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ABSTRACT

Earlier theoretical work on automatic detection by
an array or a network of arrays is extended to include
the case where the signal amplitude varies log-normally
between sensors or arrays. We find that a "multi-array"
detector which detects on the sum of the subsystem
detector outputs is substantially superior to a "voting"
detector. This result is in agreement with the few
available empirical data. We recommend that the multi-
array detector be further evaluated using empirical
data with a view to its use in worldwide networks and
in arrays with widely spaced subarrays. Several other
results are obtained which show that existing techniques
for evaluating network thresholds are accurate for
automatic detectors.

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INTRODUCTION

Seismic detection of body waves or surface waves
may be considered from the point of view either of a
single instrument, or of an array, or of a worldwide
network of arrays. Different detection techniques are
appropriate for each system because of variability in
the signal correlation. A single array may profitably
be viewed as a network of subarrays if the signals are
uncorrelated between the subarrays.

Reviews of array detection techniques have been
given by Blandford (1970, 1972) who pointed out that
a power detector and an F-statistic detector should
have approximately equal probability of detection for
a fixed false alarm rate if an array has high signal
correlation, low noise correlation, and more than six
instruments. (A power detector uses the ratio of a
short-term average of the beam power to a long-term
average, an F detector uses the ratio of the beam
power to a noise estimate computed in the detection
window.) Blandford also pointed out that for these
conditions the F-detector has certain qualitative
advantages over the power detector. Wirth, Blandford
and Shumway (1971) extended this word to the case
of a network of F-detectors which can either be
seen as an array composed of subarrays, or as a world-
wide network of arrays. Their results are generally
valid also for a network of power detectors. It has
been generally suspected from theoretical results on
detection of harmonic signals that if power estimates

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are replaced by estimates of the average rectified ampli-
tude (as is done at present for the LASA-SAAC short-
period detector) then the performance of these detectors
would not be significantly worse. This would be true
even though theory shows that the power and F-detectors,
for stationary and non-stationary noise respectively,
are maximum likelihood detectors and have the highest
possible probability of detection for fixed false alarm
rate. Husebye (1972) has indicated that the gain from
using a power detector instead of a rectifying detector
is "modest" at NORSAR.

At NORSAR one of two detectors presently in opera-
tion is the rectifying version of the "multi-array
F-detector" analyzed theoretically by Wirth et al.,
1971. This NORSAR detector has been described in two
IBM publications (1971, 1972).

It detects using a threshold on the ratio of the
short-term to long-term averages of the beam of the
rectified subarray beams. (The power detector would
square the subarray beams; the F-detector would
estimate the noise as the average residual subarray
noise power in the signal window.)

Wirth et al., 1971, showed that the multi-array F
(or power) detector would be only 4.3 dB worse at
NORSAR than a detector operating on the full array
when the signal had perfect correlation between sub-
arrays. Thus, if more than 4.3 dB signal loss occurred
between subarrays, the multi-array detector would be
better than full array beamforming. The graphs in the
two IBM publications (1971, 1972) indicate that in

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13 ABSTRACT

Earlier theoretical work on automatic detection by an array or a network of arrays is extended to include the case where the signal amplitude varies log-normally between sensors or arrays. We find that a "multi-array" detector which detects on the sum of the subsystem detector outputs is substantially superior to a "voting" detector. This result is in agreement with the few available empirical data. We recommend that the multi-array detector be further evaluated using empirical data with a view to its use in worldwide networks and in arrays with widely spaced subarrays. Several other results are obtained which show that existing techniques for evaluating network thresholds are accurate for automatic detectors.

14 KEY WORDS

Seismic Magnitude
Surface-Wave Amplitude
Body-Wave Amplitude

M_S vs m_b
Analysis of Variance

fact the rectified multi-array detector is superior in practice to full array beamforming. However, IBM also points out that the false alarm rate has not been adequately controlled in their experiments, so that as far as we know the conclusion has not been definitely established in practice.

The main purpose of this report is to complete the theoretical analysis of the power and F-detectors by including in the theory the observed fact that the signal-to-noise ratios at subarrays of an array, or of a worldwide network, have substantial variability. As we shall see, this leads to an even greater advantage for the multi-array detector and stongly suggests that its utility should be investigated using real data.

In such an investigation it will probably make little difference to the fundamental conclusions whether a rectifying, or power, or F detector is used. The important requirement is that for "multi-array" detection the output from each subarray should be added together and that a decision be made on the sum. We point out in this report that this procedure is far superior to the procedure of taking a vote among the subarrays and declaring a network detection when a specified number of votes is counted.

The basic reason for this superiority is that, due to natural variation, a signal may arrive at some station with an unexpectedly strong amplitude. In this case there is no question that the event occurred; but if one is counting votes, one vote may not be enough. If on the other hand the outputs are all added

together, then a large signal at one station may be
enough to force the average over the threshold.

At first it might seem that an analyst, viewing
at one time beams from several worldwide arrays
directed at the same point on the earth, is engaging
in a kind of voting procedure as he makes up his mind
on a detection. However, further consideration makes it
appear to us that any of a number of possible presen-
tations (resulting in greatly different numbers of
"votes") will convince him. For example he might be
convinced by a very strong arrival at one station
together with a marginal signal at one to three other
stations; or moderately good signals at two stations
with marginal signals at two others; or marginal signals
at four or five stations. Thus it seems to us that the
analyst is truly more closely approximating the maximum
likelihood detector than the voting detector.

This line of reasoning suggests that a worldwide
network system in which any good single array detection
would cause to be presented to an analyst all the
corresponding array beams, would result in close to
best possible detection. However, we shall see that
this is not true; the events which would escape the
analyst's scrutiny under this scheme are those which
are detected only marginally at several sites. We shall
see in our discussion of Figure 1 that for a four-station
network, these comprise enough events to raise the 90%
threshold with fixed false alarm rate by 0.2 m_b above
the best possible threshold. (Note that if a threshold
is <u>raised</u> then <u>fewer</u> events are detected.)   Location

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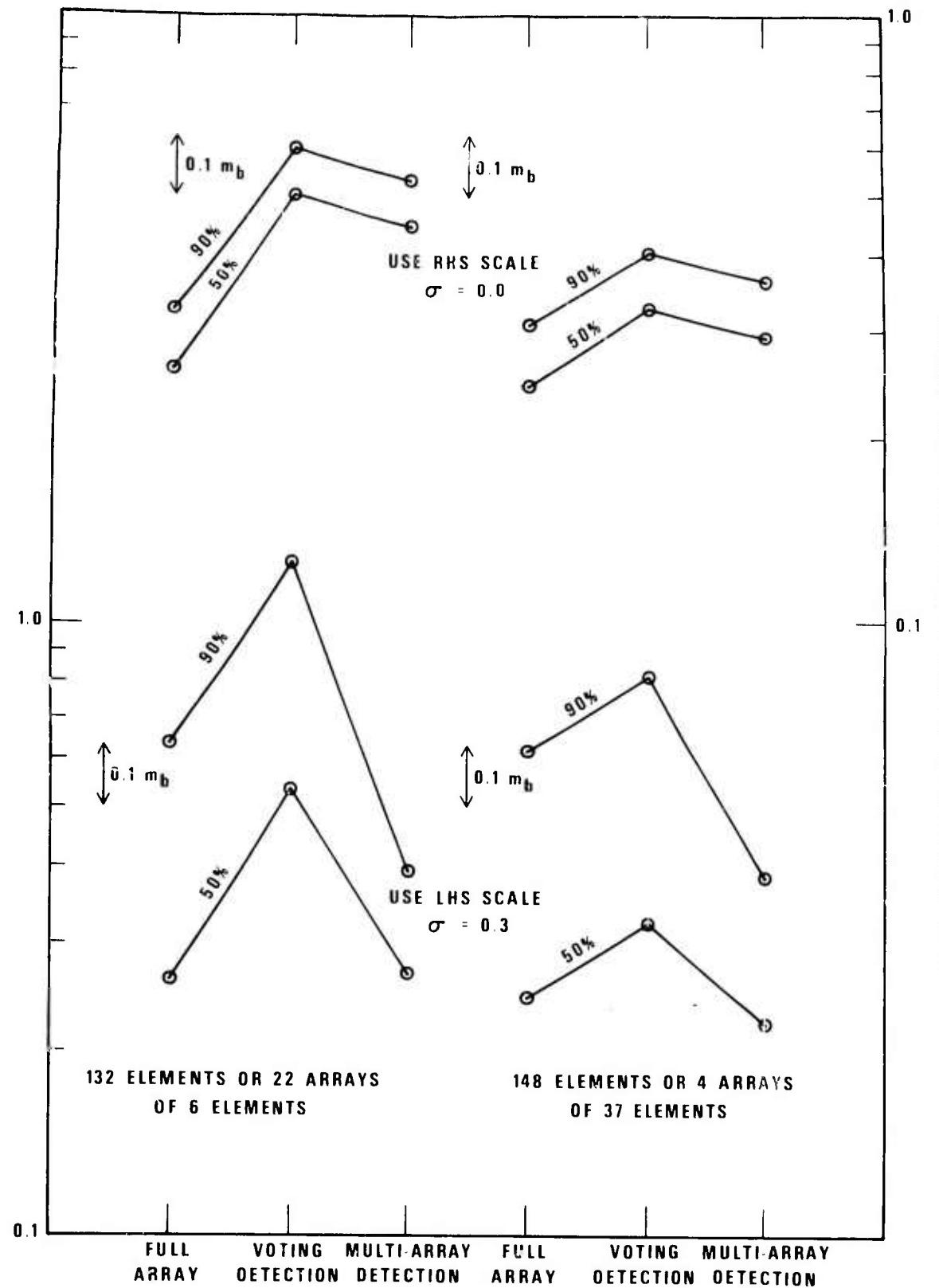
Figure 1. Signal to noise ratio (S/N) required for 90% and 50% probability of detection with 0.1 false alarms per day per beam for differing detection systems. Curves are given for σ = 0.0 and 0.3.

and discrimination would of course be difficult for these events and one might well be satisfied with this higher threshold. Nonetheless, a more advanced automatic network processor could be devised to detect these events.

If it were desired to use program FKCOMB for detection (Smart and Flinn, 1971; Smart 1973) the network detection procedure outlined above might be adopted if one could define velocity and azimuth "beams" in f-k space, and with appropriate time lags add together the powers from different arrays for significant peaks at any frequency in a broad band.

In succeeding sections we shall first outline the theoretical techniques to be used, principally those originated by Wirth et al., 1971, and follow this with a discussion of results.

THEORY AND TECHNIQUE

A simple F-detector is said to detect if $F(N_1, N_2, \lambda) \geq F_o$, where $F(N_1, N_2, \lambda)$ is the computed test statistic, assumed to belong to a population distributed as a non-central F with N_1 and N_2 degrees of freedom and non-centrality parameter λ; F_o is the threshold determined from the desired false alarm rate. Thus the probability of detection by this detector is the probability that $F \geq F_o$ in the presence of a signal. In order to make meaningful comparisons between different systems, the false alarm rate should be held constant, and this is done in all the measurements made in this report. Blandford (1970) suggests that for short-period detection, $N_1 = 2BT = 3$ is suitable, where integrated bandwidth $= B = 0.5$ Hz, and the signal window $= T = 3.0$ seconds. Theory shows that $N_2 = 2BT(N-1)$, where N is the number of elements in the array. The probability of a false alarm is the probability that $F > F_o$ with $\lambda = 0$.

For the voting detector we need to know the probability of at least K detections out of M, which is given by the summed binomial distribution:

$$P_r(\text{at least K}) = \sum_{i=K}^{M} \binom{M}{i} p^i (1-p)^{M-i} \qquad (1)$$

This formula is used to evaluate either the false-alarm rate or the signal detection probability, and p is accordingly computed from a central F or a non-central F, respectively.

The optimum value for K is determined by drawing the receiver operating characteristic curves for several values of K for a fixed S/N value, and choosing the curve which is best near an operating point of interest. Such a point might be 90% detection with 0.1 false alarms per day.

The multi-array detector is another approach possible when signals are not the same on all subarrays, and is a special case of a technique of Shumway (1970). We consider the model representing the output from the i'th sensor on the j'th subarray as

$$y_{ji}(t) = a_j S_j(t) + n_{ji}(t) \tag{2}$$

where $j = 1,\ldots,M$; $i = 1,\ldots,N$; and $t = 0, 1,\ldots,L-1$. We assume the noise $n_{ji}(t)$ to be normally distributed, stationary, and uncorrelated between sensors, and the signals S_j to be the same on all sensors of a given subarray. We further assume the S_j all to have the same rms value over time and explicitly allow for different signal size by inclusion of the factors a_j, which may be assumed to be known. Then, following Shumway (1970), the maximum likelihood estimate for the signal on the j'th subarray is just

$$\hat{S}_j(t) = a_j^{-1} y_{j.}(t) \tag{3}$$

where the dot signifies the subscript over which the mean is taken. An approximation to the F statistic is given by the sum of the beam powers divided by the sum of the residual powers, i.e.

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$$F_{2BTM, 2BTM(N-1)} \approx \frac{(N-1)N \sum_j \sum_t \bar{y}_j^2(t)}{\sum_j \sum_t [\sum_i y_{ji}^2(t) - N \bar{y}_j^2(t)]} \qquad (4)$$

where B is the filter bandwidth in Hertz, T the length of the time window in seconds, M the number of subarrays, and N the number of elements/subarray. As mentioned in Wirth et al., 1971, both signal and noise should in practice be normalized by a long-term average of the noise, perhaps over one hour. In the presence of signal, the non-centrality parameter is

$$\lambda = N_1 \left(\sum_{j=1}^{M} a_j^2 / M \right) (S/N)_{beam}^2 \qquad (5)$$

where $N_1 \equiv 2BTM$ is the number of degrees of freedom of the numerator and $(S/N)_{beam}$ is the signal-to-noise ratio on the subarray beam divided by a_j. Throughout this report (S/N) is expressed as the square root of the quantity signal power divided by noise power. An approximate empirical factor for converting rms ratios to peak-to-peak signal over peak-to-peak noise for short period P signals of specified shape as seen through a near-optimum detection filter is 0.5, (Blandford, 1970). When M = 1, the detector reduces to the single-array F detector.

In analyzing NORSAR, Wirth et al., 1971, assumed that a_j = 1.0 for each of the 22 subarrays. In fact we know that at LASA (Klappenberger, 1967) and at NORSAR (Husebye, 1972) the distribution of signal amplitudes is log-normal. Thus the distribution of λ

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in (5) is given by the distribution of a sum of log-
normal variables squared. To take account of this fact
for calculating receiver operating characteristic curves
it is only necessary to modify the computer programs
discussed by Wirth et al., 1971, so that the probability
of detection is given by an integral with respect to λ
of the probability of detection given λ, times the
probability of λ.

The probability distributions required for the sum
of log normals were determined by simulations in which
7200 random numbers were used to compile the histogram.
Repetitions of the numerical integrations with new sets
of random numbers and with refined spacings for the
integrals with respect to λ ensured that the threshold
signal-to-noise values reported are accurate to better
than 1%.

The algorithms for these computations are fully
discussed in Wirth et al., 1971.

RESULTS

Tables I and II present the principal results of this report in tabular form. The entries are derived by graphical linear interpolation on the graphs in the appendix. Table I is for networks (or arrays) of 2-4 subarrays of 37 elements each (e.g., TFO). Table II is for 22 or 7 subarrays of six elements (LASA or NORSAR, possibly reduced). The cases of a full array with perfect correlation of the signal between subarrays, an optimum K or voting detector, and the multi-array detector are considered. The standard deviation of the logarithm of the signal to noise ratio is assumed to be either $\sigma = 0.0$ or 0.3.

In the table column headings, M denotes the number of subarrays, K is the optimum number of detecting sub-arays for the voting detector, NI is the total number of instruments in the full array, N1 is the number of degrees of freedom in the numberator, and N2 is the number of degrees of freedom in the denominator of the F statistic. Note that the optimum value for K is the same for $\sigma = 0.0$ and $\sigma = 0.3$. It is not at all obvious that this should be the case, but this is the result. For $\sigma = 0.3$, however, the choice of a non-optimum K is far less costly than for $\sigma = 0$. $(S/N)_{beam}$ is the log-normal mean signal-to-noise ratio on the beam of the largest array which has been assumed to have a perfectly correlated signal. For the cases of a full array with perfect correlation this would then correspond to the signal-to-noise ratio on the beam of an

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TABLE I

Signal to Noise Ratio Required for Detection by Various Systems for σ = 0.0, 0.3

37 elements/array; 1, 2, 3, 4 stations; 2BT = 3.

Thresholds for 90% detection at 0.1 FA/day/beam

σ = 0

	M	K	NI	N1	N2	S/N beam	S/N seis	Appendix A Figure No.
Full Array Perfect Correlation	1	-	37	3	108	3.96	.650	1
	2	-	74	3	219	3.86	.449	2
	3	-	111	3	330	3.78	.359	3
	4	-	148	3	441	3.76	.309	4
"Voting" or Optimum K	2	2	74	3	108	3.15	.518	5
	3	2	111	3	108	2.78	.457	6
	4	3	148	3	108	2.48	.408	7
Multi-Array F	2	-	74	6	216	2.91	.478	8
	3	-	111	9	324	2.47	.406	9
	4	-	148	12	432	2.20	.362	10

σ = .3

	M	K	NI	N1	N2	S/N beam	S/N seis	Appendix A Figure No.
Full Array Perfect Correlation	1	-	37	3	108	7.91	1.30	11
	2	-	74	3	219	7.71	.896	12
	3	-	111	3	330	7.60	.721	13
	4	-	148	3	441	7.55	.621	14
"Voting" or Optimum K	2	2	74	3	108	6.05	.995	15
	3	2	111	3	108	5.58	.913	16
	4	3	148	3	108	4.98	.820	17
Multi-Array F	2	-	74	6	216	3.98	.653	18
	3	-	111	9	324	2.84	.467	19
	4	-	148	12	432	2.35	.386	20

TABLE II

Signal to Noise Ratio Required for Detection by Various
Systems for σ = 0.0, 0.3

6 elements/array; 7 and 22 stations; 2BT = 3.

Thresholds for 90% detection at 0.1 FA/day/beam

σ = 0

	M	K	NI	N1	N2	S/N beam	S/N seis	Appendix A Figure No.
Full Array Perfect Correlation	7	-	42	3	123	3.92	.602	21
	22	-	132	3	393	3.77	.528	22
"Voting" or Optimum K	7	5	42	3	15	2.28	.930	23
	22	12	132	3	15	1.47	.600	24
Multi-Array F	7	-	42	21	105	2.02	.825	25
	22	-	132	66	330	1.30	.530	26

σ = 0.3

	M	K	NI	N1	N2	S/N beam	S/N seis	Appendix A Figure No.
Full Array Perfect Correlation	7	-	42	3	123	7.68	1.19	27
	22	-	132	3	393	7.30	.635	28
"Voting" or Optimum K	7	5	42	3	15	4.64	1.90	29
	22	12	132	3	15	3.11	1.27	30
Multi-Array F	7	-	42	21	105	1.82	.743	31
	22	-	132	66	330	.96	.39	32

array of 37, 74, 111, or 148 elements for Table I; and
42 and 132 elements for Table II. For the voting or
multi-array detector the beam signal-to-noise value is
for an array of 37 elements for Table I and six elements
for Table II. The signal-to-noise ratio at the seismo-
meter level, $(S/N)_{seis}$, is calculated by dividing the
$(S/N)_{beam}$ by the square root of 37, 74, 111, or 148; 6,
42 or 132 as appropriate.

The numbers of the figures in the Appendix
corresponding to each case is given in the last column.
The signal-to-noise values on these figures are for
the beam.

Note that $(S/N)_{seis}$ is the parameter required to
determine the detection threshold of the full array
or network.

All of the results in this report are quoted for
0.1 false alarms (FA) per day per beam. At LASA-SAAC
with 600 beams this would imply a total number of 60
false alarms per day. At present the Detection
Processor runs at a rate of 22 detections per hour
or 528 per day. Only about 35 of these are accepted
as true events, so that LASA-SAAC detection processor
is at present probably running at ten times the false
alarm rate assumed in this report. Most of these
"detections" are, however, discarded by means of a
higher threshold, so the analysts are really only
confronted with about 60 evaluations per day, a
comparable number to that used here. For

long-period detections in a small predicted time window, a higher false alarm rate might be tolerated.

Some discussion of the physical models underlying the mathematics would be useful at this point.

1. A full array with perfect correlation and $\sigma = 0$ could be regarded as an array of instruments so closely spaced that there are not amplitude anomalies between them. Furthermore, it would have to be in a remarkably stable noise environment, and detecting events from a very small source region so that from event to event there is no variation due to amplitude anomalies.

2. A full array with perfect correlation and $\sigma = 0.3$ could be regarded as an array of instruments so closely spaced that there are no amplitude anomalies between them; but in a noisy environment and looking at a large enough source region that the square root of the sum of the squares of the noise and signal variances is 0.3. Note that larger values of σ than 0.3 might easily be appropriate; for example if the noise and signal standard deviations were each 0.3.

3. A voting or multi-array detector with $\sigma = 0.3$ could be regarded as a worldwide network of "small" arrays such that the square root of the sum of the squares of the inter-array noise and signal variances is 0.3. As in (2) this number could be larger.

4. A voting or multi-array detector with $\sigma = 0.3$ can be regarded as an array of subarrays for which the square root of the inter-subarray noise and signal

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variance sum is 0.3. In the context of the formal theory presented here one cannot include in this variance the noise and signal variances between arrays. These variances would raise the 90% threshold in actual operation. If we assume that the "external" variances sum to $(0.3)^2$, then the discussion to come in connection with Figure 2 suggests that the 90% threshold will be raised by $0.1 - 0.2$ m$_b$ and that the 50% threshold will be essentially unchanged.

On the other hand, the voting or multi-array detector at LASA or NORSAR might require only ten or twenty out of 600 or about 1/30th as many beams so that the false alarm rate per beam could be raised by a factor of 30, thus lowering the array 90% threshold. Inspection of Figure A-32 suggests that the decrease in number of beams would result in lowering the 90% and 50% thresholds by 0.04 m$_b$.

Using these estimates we can draw some conclusions about the relative performance of the full array, voting, and multi-subarray detectors by taking the "external" variances and the number of beams into account as needed. We should also keep in mind that for an array where the voting or multi-subarray detector would be considered, several dB would be lost on the array beams.

From Figure 1 we may draw the following conclusions:
1. As stated in Wirth et al., 1971, for 22 subarrays of six elements each (such as NORSAR) with $\sigma = 0$, the voting and multiarray detector are 0.27 and 0.215 m$_b$ worse, respectively, than the full array operating with perfect correlation. This tells us that for a compact

array such as TFO we would expect to lose on the order of 0.2 m_b in sensitivity if we were to treat subsets of seismometers as subarrays and use a voting or multi-array detector.

2. The difference between the 90% and the 50% thresholds is greater for $\sigma = 0.3$ than for $\sigma = 0.0$; typically 0.2 - 0.4 m_b versus 0.08 - 0.11 m_b. This is in accordance with our expectations from NETWORTH calculations (Wirth, 1970). We shall see below that the automatic detectors fit the NETWORTH hypotheses in a natural way, so that NETWORTH predictions are highly accurate.

3. The voting detector is worse than either of the other detectors, and gets progressively worse as σ increases. This is in agreement with the conclusion by Wirth et al., 1971, that as the a_j values in equation (2) depart from 1.0, the multi-array detector's superiority over the voting detector increases.

The voting detector with $K = 1$ is the model for the detection strategy outlined in the Introduction where detection at any array leads to presentation of all beams to an analyst. If we assume that the analyst detects perfectly on the events with which he is presented, and rejects all false alarms, he cannot surpass the $K = 1$ detector. For four stations, $\sigma = 0.3$, the system will be ~ 0.2 m_b worse than a system in which the multi-array automatic detector is used to decide what windows are presented to the analyst; here again assuming that the analyst performs perfectly on the data presented to him. However, the weaker events with no outstanding station

detection may prove more difficult to analyze.

4. If $\sigma = 0.3$ the multi-array processor is about $0.2\ m_b$ better in detection than beamforming the perfect correlated data at the 90% level, and approximately equal in capability at the 50% level. In application to a large array such as LASA or NORSAR, in our analysis of Figure 2, we will see that we must remove $0.13\ m_b$ capability from the multi-array capability at 90%, and add $0.04\ m_b$ capability at 50%. We must then consider that $0.1 - 0.2\ m_b$ (2-4 dB) are lost at LASA and NORSAR in full array beamforming due to signal loss between subarrays. Thus it appears that the multi-array processor should be $0.2\ m_b$ better in practice than simple full array beamforming if $\sigma = 0.3$ is realistic between subarrays at LASA and NORSAR.

5. At 90% probability the multi-array processor with $\sigma = 0.3$ is about $0.08 - 0.09\ m_b$ worse in detection than the full array detector with $\sigma = 0$. This reinforces the common-sense conclusion that it would not be wise, for example, to split up TFO into six widely separated subarrays and use the multi-array detector in hopes of improving the threshold. At 50% probability, however, there does seem to be some possibility that the overall performance would not be noticeably changed by this procedure.

Figure 2 can be analyzed to show that the assumptions in NETWORTH (Wirth, 1970) are realistic for automatic detectors. In that program it is assumed that at a single station there is a threshold signal-to-noise
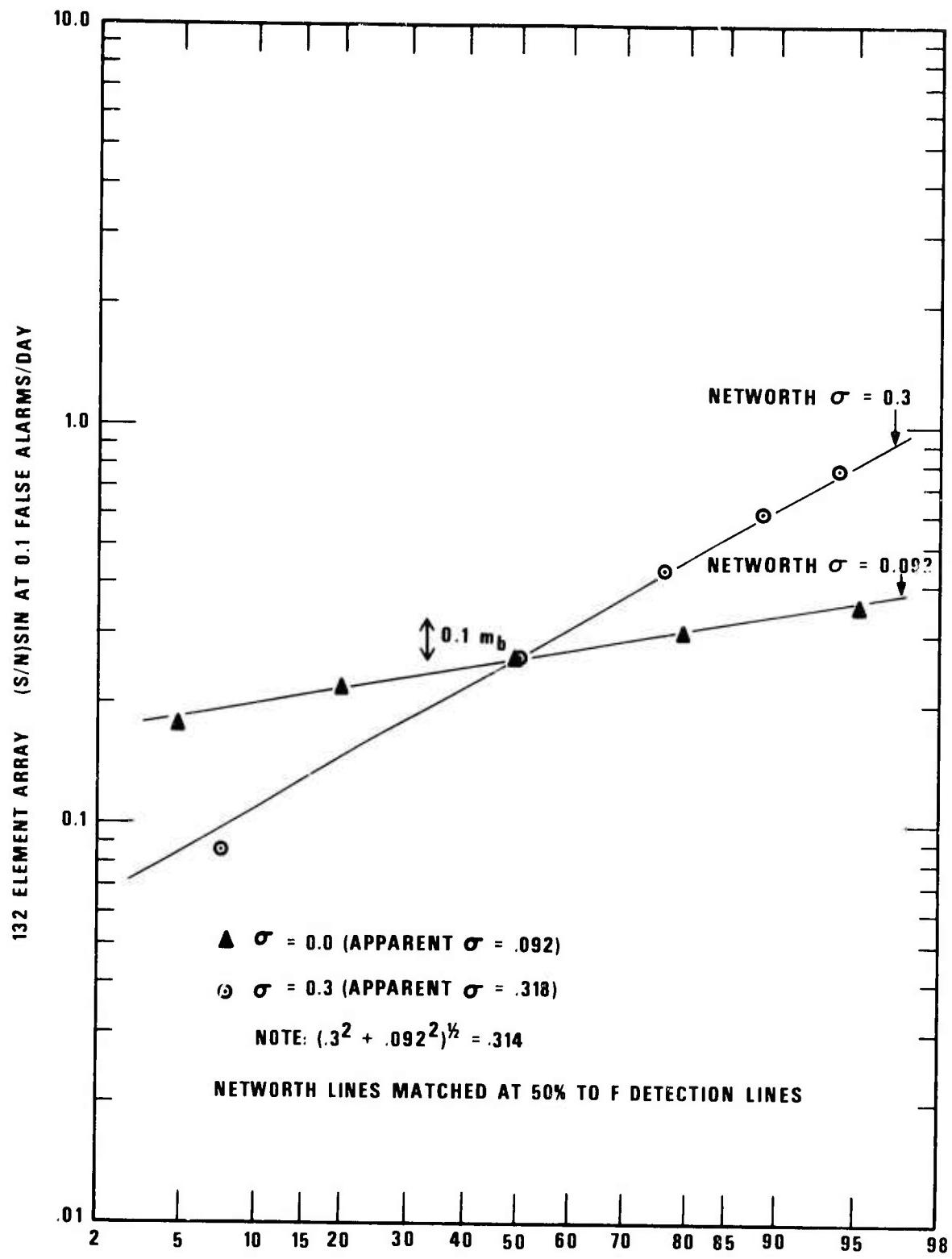
Figure 2. Signal to noise ratio (S/N) required for detection at various probability levels for full arrays with $\sigma = 0.0$ and 0.3. For $\sigma = 0.3$ the (S/N) required for 90%, 50%, and 10% detection is greater, equal to, and less than that required for $\sigma = 0.0$

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ratio and that detection is 100% certain above that ratio, and impossible below that ratio. This is obviously an approximation, but if the actual detection curve is sharp enough it would be satisfactory. The triangles in Figure 2 show the probability of detection as a function of $(S/N)_{seis}$ for a single array of 132 elements with $\sigma = 0$. The slope of this curve would be the same for a power detector on either a single element or an array of 132 elements. This analysis will be valid for these detectors also. We note first that the traingles nearly follow the straight line which they would follow for a "NETWORTH" detector with $\sigma = 0.092$. Thus an automatic detector in an environment with no noise or signal variance could be modeled quite accurately in NETWORTH simply by assuming $\sigma = 0.092$.

The circled points occur when we set $\sigma = 0.3$ (Figure A-28). We see in Figure 2 that a NETWORTH line, fitted at 50% and with $\sigma = 0.3$, is a good approximation to these points. The best straight-line approximation, drawn by eye, has $\sigma = 0.318$, and we note that $(0.3)^2 + (0.092)^2 = (0.314)^2$. Thus it appears that to a very good approximation, NETWORTH calculations appropriate to automatic detection may be made for arrays with perfect signal correlation simply by adding the calculated variance appropriate to the $\sigma = 0$ case for automatic detection to the noise and signal variances. The correction discussed in paragraph 4 above is obtained by estimating σ from a graph, much like Figure 2, which includes the between subarray variance, and calculating the total σ_t as $\sigma_t^2 = \sigma^2 + \sigma_e^2$ where σ_e^2 is the "external" (S/N) variance.

It is also worth noting that in Figure 2 as σ changes from 0.0 to 0.3 the 50% point remains perceptibly unchanged, while the 10% threshold decreases. This behavior also is exactly as predicted by the NETWORTH model. For the 50% point $(S/N)_{beam} = 3.0$, which when converted to peak-to-peak signal over peak-to-peak noise by multiplying by 0.5 (Blandford, 1970) yields 1.5. We see now that this implies a tolerable false alarm rate about equal to that in the existing LASA-SAAC system. A value near 1.5 has also been obtained by Geotech (1966) by evaluating the detection threshold of human analysts on short-period signals imbedded in noise. The analyst's false alarm rate was, however, not evaluated.

IMPLICATIONS AND SUGGESTIONS FOR FURTHER RESEARCH

Both theory and observation indicate that voting
detectors are substantially inferior in pure detection
to other types of detectors. Implementation of such
detectors should therefore be subject to careful
scrutiny to determine some reason why these theoretical
and observational results do not apply, or are
irrelevant. The latter might be true if poor signal-to-
noise ratio detections are not useful.

The multi-array detectors, show promise, from both
the theoretical and observational point of view and the
next step in research should be evaluation using
empirical data. Application may be made to large arrays
of dispersed subarrays and to continental and worldwide
networks of arrays. It is worth noting that a set of
LASA subarrays could simulate a worldwide network of
arrays. Using data already recorded, a study could be
made of completely automatic multi-array detection
followed by presentation to a seismic analyst; or of
the technique discussed in the Introduction, in which
a detection at any station causes the corresponding
time periods to be presented to an analyst, who makes
a "multi-array" detection.

It would be useful to use only a small subset of
the LASA subarrays for these experiments (perhaps the
four F-ring subarrays) so that the full LASA could be
used as a standard, alleviating the troublesome problems
of "true" and "false" false alarms.

Long-period detection could be examined from a

similar point of view and is probably more important.
We should emphasize that it is not at all necessary to
use an F-detector as the subarray detector. Thus the
four F-ring vertical seismometers could simulate four
independent stations using power detectors on match-
filtered traces, for example, and their capability
could be compared to the full LASA.

The value of the detection statistic automatically
determines an estimated signal amplitude which can be
used for M_s - m_b purposes; however, it may be objected
that the additional detections which the multi-array
detector yields will be of little value since on no
single beam will the signal-to-noise value be great
enough to pick time and sign of first motion, or to
perform cepstral analysis, spectral splitting, etc. We
feel that the situation is not uniformly bad, and
that each case needs to be examined individually on
its merits. For example, consider the case of the
multi-array detector for the short-period NORSAR array.
From Table II we see that the full array beam signal-
to-noise ratio for an event detected at the 90% level
by the multi-array detector will be $(7.30) \times (0.39/0.635) =$
4.48. On the multi-array detector the average value
will be 0.96; but of the 22 subarrays with a standard
deviation of 0.3 we would expect the highest signal-to-
noise value to be at about the 95% point of the distri-
bution, i.e., $0.96 \times 10^{0.3 \times 1.65} = 3.00$. Thus there is
an apparent loss, from 4.48 to 3.0, of 3.4 dB in
signal-to-noise ratio. However, we must remember that
the array beam itself at NORSAR has very likely lost
3 - 4 dB of signal, according to Barnard and

Whitelaw (1972). Thus the signal-to-noise ratio traces available might be expected to be about equivalent. The best subarray could be automatically determined by the detection process, so that a good signal-to-noise trace would in fact be available. In support of this we have examined the LASA event processor plots at SAAC for a day picked at random (August 1, 1972). For those events with filtered array beam peak-to-peak signal over peak-to-peak noise ratios of about 10, the best filtered subarray beam was only 3 dB worse than the filtered array beam on the average. At NORSAR the same values are apparently typical (Figure IV-5, Barnard and Whitelaw, 1972).

As a final example, consider the case of network detection. Definite detections which are poorly located because of low signal-to-noise values may still turn out to be in aseismic regions, or for other reasons spur examination of regional data in an off-line mode.

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REFERENCES

Barnard, T.E. and Whitelaw, R.L., 1972, Preliminary
    evaluation of the Norwegian short period array:
    Special Report No. 6, Extended array evaluation
    program, Texas Instruments Services Group,
    Dallas, Texas.*

Blandford, R.R., 1970, An automatic event detector at
    TFO: Seismic Data Laboratory Report No. 263,
    Teledyne Geotech, Alexandria, Virginia. (AD881923)*

Blandford, R.R., 1972, Qualitative properties of the
    F-detector: Seismic Data Laboratory Report No. 291,
    Teledyne Geotech, Alexandria, Virginia. (AD753 059)*

Geotech, 1966, Estimates of the detection capability of
    four Vela-Uniform seismological observatories:
    Technical Report 66-1, Teledyne Geotech, Garland,
    Texas.

Husebye, E.S., 1972, NORSAR research and development
    (1 July 1971 - 30 June 1972): NORSAR Report No. 50
    Royal Norwegian Council for Scientific and
    Industrial Research, Kjeller, Norway.

IBM, 1971, Integrated seismic research signal processing
    system: IBM Final Technical Report, Contract
    F19(628)-68-C-0400, ESD-TR-72-139.*

IBM, 1972, Seismic array design handbook, Contract
    F19628-68-C-400, Federal Systems Division, IBM,
    Gaithersburg, Maryland.*

Klappenberger, F.A., 1967, Distribution of short-period
    P-phase amplitudes over LASA: Seismic Data Laboratory
    Report No. 195, Teledyne Geotech, Alexandria, Virginia.
    (AD819 938)*

REFERENCES (Cont'd.)

Shumway, R.H., 1970, Applied regression and analysis
of variance for stationary time series: J. Am.
Stat. Assoc., v. 65, p. 1527-1546.

Smart, E. and Flinn, E.A., 1971, Fast frequency-wavenumber
analysis and Fisher signal detection in real-time
infrasonic array data processing: Geophys. J.R.
Astr. Soc., v. 26, p. 279-284.

Smart, E., 1973, FKCOMB, A fast general-purpose processor
for digital array data: Seismic Array Analysis
Center Report No. 9, Teledyne Geotech, Alexandria,
Virginia.*

Wirth, M.H., Blandford, R.R. and Shumway, R.H., 1971,
Automatic network detection: Seismic Data
Laboratory Report No. 285, Teledyne Geotech,
Alexandria, Virginia. (AD 737 129)*

Wirth, M.H., 1970, Estimation of network detection and
location capability: Seismic Data Laboratory
Research Memorandum, Teledyne Geotech, Alexandria,
Virginia.

*Available from the National Technical Information Service,
U.S. Department of Commerce, Springfield, Virginia 22151.

APPENDIX

-28-

The following 32 figures give false alarms per day as a function of probability of detection for several values of the signal-to-noise ratio. The system to which each figure refers.may be determined by reference to Tables I and II in which each line is keyed to the appropriate figure number.

FALSE ALARMS/DAY vs PROBABILITY OF DETECTION - %

S/N = 2.00
S/N = 2.50
S/N = 3.00
S/N = 3.50
S/N = 4.00

M = 1
NI = 37
N1 = 3
N2 = 108

-A1-

S/N = 1.50

S/N = 2.00

S/N = 2.50

S/N = 3.00

M = 2
K = 2
NI = 74
N1 = 3
N2 = 108

FALSE ALARMS/DAY

PROBABILITY OF DETECTION - %

-A5-

S/N = 1.50

S/N = 1.75

S/N = 2.00

S/N = 2.25

S/N = 2.50

S/N = 2.75

M = 3
K = 2
NI = 111
N1 = 3
N2 = 108

FALSE ALARMS/DAY

PROBABILTY OF DETECTION - %

-A6-

FALSE ALARMS/DAY vs PROBABILITY OF DETECTION - %

S/N = 1.00
S/N = 1.50
S/N = 2.00
S/N = 2.50
S/N = 3.00

M = 2
NI = 74
N1 = 6
N2 = 216

PROBABILITY OF DETECTION - %

(Y-axis label: FALSE ALARMS/DAY)

Contour labels:
S/N = 1.25
S/N = 1.50
S/N = 1.75
S/N = 2.00
S/N = 2.25
S/N = 2.50
S/N = 2.75

M = 3
NI = 111
N1 = 9
N2 = 324

-A12-

FALSE ALARMS/DAY

PROBABILITY OF DETECTION - %

S/N = 1.00

S/N = 3.00

S/N = 5.00

S/N = 7.00

S/N = 9.00

M = 3
NI = 111
N1 = 3
N2 = 330

-A13-

FALSE ALARMS/DAY

S/N = 1.00

S/N = 3.00

S/N = 5.00

S/N = 7.00

S/N = 9.00

M = 4
NI = 148
N1 = 3
N2 = 441

PROBABILITY OF DETECTION - %

-A14-

-A15-

-A17-

-A19-

FALSE ALARMS/DAY vs PROBABILITY OF DETECTION - %

S/N = .50
S/N = 1.00
S/N = 1.50
S/N = 2.00
S/N = 2.50
S/N = 3.00

M = 4
NI = 148
N1 = 12
N2 = 432

FALSE ALARMS/DAY vs PROBABILITY OF DETECTION - %

Curves labeled S/N = 2.00, S/N = 2.50, S/N = 3.00, S/N = 3.50, S/N = 4.00, S/N = 4.50

M = 7
NI = 42
N1 = 3
N2 = 123

FALSE ALARMS/DAY vs PROBABILITY OF DETECTION - %

S/N = 2.00
S/N = 2.50
S/N = 3.00
S/N = 3.50
S/N = 4.00

M = 22
NI = 132
N1 = 3
N2 = 393

-A22-

PROBABILITY OF DETECTION - %

-A24-

FALSE ALARMS/DAY (y-axis), PROBABILITY OF DETECTION - % (x-axis)

S/N = 1.00
S/N = 1.25
S/N = 1.50
S/N = 1.75
S/N = 2.00

M = 7
NI = 42
N1 = 21
N2 = 105

FALSE ALARMS/DAY vs PROBABILITY OF DETECTION - %

Curves labeled:
S/N = 1.00
S/N = 3.00
S/N = 5.00
S/N = 7.00
S/N = 9.00

M = 22
NI = 132
N1 = 3
N2 = 393

-A30-